A Design on Integrated Protocol for Communications and Positioning

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Abstract - The purpose of this paper is to introduce an integrated protocol for communications and positioning. The motivation for designing this integrated protocol comes from the recent research results for using location information. The objective of the integrated protocol is to enable simultaneous data exchange and location discovery. We describe the protocol stack of the integrated protocol and look at the facilities required for each layer. For the MAC layer, resource control for positioning is introduced. For the NWK layer, simultaneous localization and routing is discussed. Target tracking, an application of the integrated protocol, is also investigated.

Keywords: positioning, data communications, wireless multi-hop networks, ad-hoc networking

1 Introduction

Emerging wireless networking capabilities and micro-electronics technologies enable the provision of the various types of networks, such as ad-hoc and sensor networks. Zigbee [1] is one of these emerging standardized sensor network products. Once sensor nodes are deployed, they can automatically gather the sensing information for a observer. In such sensor networks, sensing data is expected to be bundled with location information to locate the event. To know the node positions, positioning techniques have been discussed in areas such as cellular communications [3] and wireless multi-hop networks [4].

The relationship between data communication protocols and positioning protocols is shown in Fig. 1. Location information is not only used for sensor networks, but also for improving networking performance. Location information helps to reduce redundant packets [12], [13]. In location-aided routing (LAR) [13], the expected zone based on the location of a destination node is defined to reduce packet flooding. A number of redundant packets is dropped by limiting the flooding zone.

In addition, location information contributes to improving energy efficiency. In geographical adaptive fidelity (GAF) [14], nodes can go to sleep to conserve energy. Since GAF defines the virtual grid based on the location information to find the nodes necessary for data delivery, it can maintain the data delivery over an extended network life time.

Another application of location information is in medium access control (MAC) protocol for collision avoidance. Location information enables nodes to know the direction of their neighbor nodes. In this case, the wireless communication range can be shrunk to avoid media access collision. In

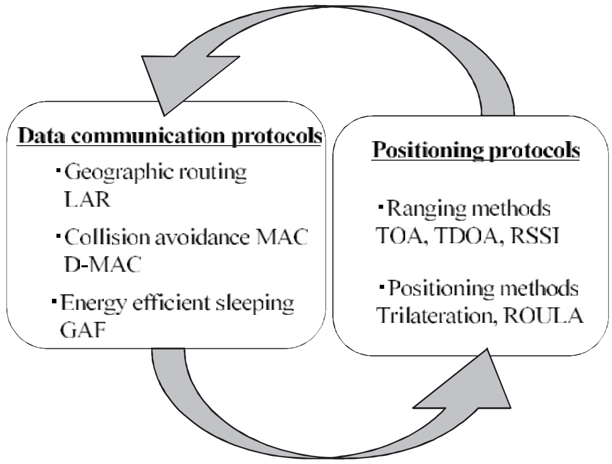

Figure 1: Relationship between data communication and positioning protocols.

[15], the authors proposed that a node sends packets by using a limited wireless range with a directional antenna to a receiver when the transmitter knows the receiver's location.

While location information is useful for data communication protocols, a positioning protocol that provides node positions must be able to obtain location information anywhere. As discussed in a lot of different literature, the global positioning system (GPS) is a simple solution for obtaining node positions. However, GPS cannot always provide location information, such as inside buildings.

A positioning protocol consists of two steps. First is estimating the distance (or ranging) by using time-of-arrival (TOA), time difference of arrival (TDOA), or received signal strength indicator (RSSI). Second is positioning the nodes to calculate the coordinates. Positioning methods for wireless multi-hop networks have been previously discussed [16], [17].

To enable nodes to obtain their positions at any place, a positioning protocol is required. The positioning protocol itself requires an overhead of ranging message that includes communicating nodes. Therefore, it is inefficient to design each data communication protocol and positioning protocol separately. Therefore, we designed an integrated data communication and positioning protocol.

ISSN1883-4566/09

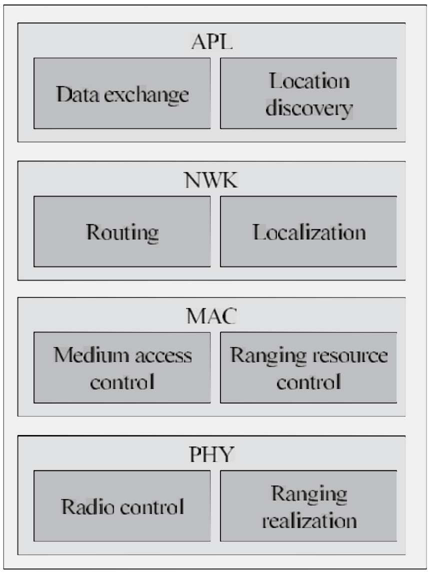

Figure 2: Protocol stack of integrated protocol for communications and positioning.

1.1 Outline of paper

Section 2 describes an overview of the integrated protocol for communications and positioning. The physical layer (PHY) and MAC layer are described in Section 2.2 and 2.3, respectively. Section 2.4 presents an overview of the network (NWK) layer, including an issue of the layer and our solution.

Target tracking which is an application of the integrated protocol is introduced in Section 3. A problem statement of target tracking is given in Section 3.1. We also propose cooperative target tracking method that uses the ranging capability in Section 3.2. The performance of cooperative target tracking is evaluated in Section 4.

Section 5 summarizes the paper and mentions our future work.

2 Integrated protocol for communications and positioning

2.1 Overview

The integrated protocol for communications and positioning is operated under wireless multi-hop network topology.

The protocol stack of the integrated protocol is shown in Fig. 2. The objective of the integrated protocol is to enable simultaneous data exchange and location discovery. It enables users to obtain data and location information in the application layer (APL).

To enable data communications, each layer has conventional data communication facilities. Ranging realization, ranging resource control, and localization are added to support location discovery. We then describe functionalities of the PHY, MAC, and NWK layers.

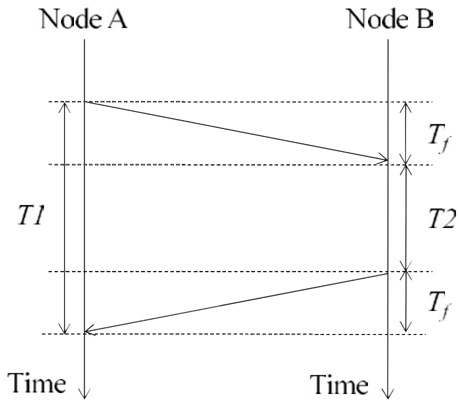

Figure 3: Ranging message sequence for TW-TOA.

2.2 PHY

Ranging realization is achieved in the PHY. IEEE 802.15.4a [9] standardized the ranging capabilities, which enable the nodes to estimate the node distance, although the implementation is optional. We then use the same mechanism of ranging capabilities as described in IEEE 802.15.4a specification.

Figure 3 shows the message sequence for the ranging realization by using a two-way time-of-arrival (TW-TOA) between two nodes, A and B. The propagation time T_f to estimate the node distance can then be written as

$$T_f = \frac{1}{2}(T1 - T2), \tag{1}$$

where $T1$ is the round trip time for node A and $T2$ is the reply time for node B. Here, we only consider the true times of the message arrivals. A distance can be derived from the propagation time, and TW-TOA enables the estimation of the node distance. TW-TOA can be achieved by observing the first arrival signal of the received signals, and it requires at least two messages between nodes.

One notable observation on the IEEE 802.15.4a specification is that it enables the node to estimate distances in the PHY. However, IEEE 802.15.4a does not support a positioning functionality. Therefore, a facility to calculate the node position is required to be defined on an upper layer.

2.3 MAC layer

Figure 4 shows the time slots in the MAC protocol for the integrated protocol. The ranging capability enables the tracking and navigation applications. In such applications, data may be needed to be sent without collisions. The functionality in the MAC layer is to schedule and control the ranging resource to conduct the tracking and navigation applications. The contention access period (CAP) is collision-based packet scheduling, and the contention free period (CFP) is collision-free packet scheduling, which is the same mechanism as described in IEEE 802.15.4 [8] specification. Although CFP is required to the synchronization between nodes, data can be sent without collision. The CFP provide a guaranteed time

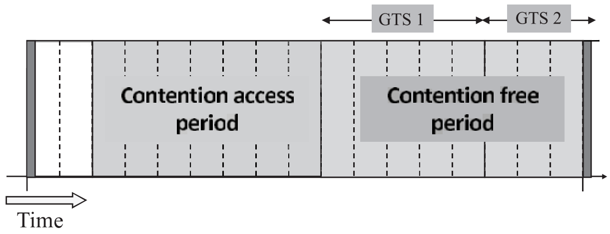

Figure 4: Time slots in MAC protocol for integrated protocol.

slot (GTS) to send packets periodically. Thus, CFP can be used for the tracking and navigation applications.

A challenging functionality for the MAC protocol is to design a mechanism to assign the time slot to send data with the precise positioning accuracy. In existing data communication protocol, delay and reachability are parameters to indicate the quality of service (QoS). Then the nodes will cooperate for improve the delay or reachability. In the integrated protocol, positioning accuracy is the parameter to indicate the QoS. Each time slot in the MAC layer is selected and scheduled in terms of the precise positioning accuracy. Then nodes will cooperate for precise positioning accuracy.

Figure 5 shows the example data relaying when three wireless nodes $A, B,$ and C are connected in the networks. Assume that node A will deliver the data to the node B. When latency for the data delivery is critical for the network, node A directly send the data to the node B. However consider that when an obstruction is existed between A and B and node distances are required to being precisely measured for the positioning. The distance measurement between A and B is degraded for the non-line-of-sight (NLOS). In this case, node A should use the node C to precisely measure the distances for node B. Therefore, a node has to change the destination for data relaying when data and positioning requests are mixed. The data flows are required to be controlled in accordance with QoS priority. We will present the case that nodes should cooperatively relay for precise positioning in a target tracking in Section 3. The simulation results presented in Section 4 reveal that the cooperative relaying through a line-of-sight (LOS) link improves the positioning accuracy.

2.4 NWK layer

The NWK layer provides the simultaneous routing and localization capability. The localization protocol estimates node positions. The motivation for developing localization protocol is wanting to know the node positions in multi-hop networks with only a small number of anchor nodes. An anchor node is one whose position is known in advance through such as GPS.

We previously developed optimized link state routing-based localization (ROULA) [17]. ROULA is independent of anchor nodes and can determine the correct node positions in a non-convex network topology. In addition, ROULA is compatible with the optimized link state routing (OLSR) protocol [21] and uses the inherent distance characteristic of multipoint relay (MPR) nodes.

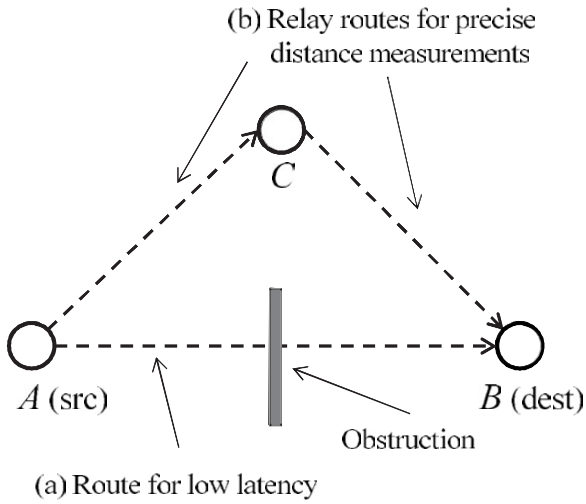

Figure 5: Example data relaying for (a) low latency and (b) precise distance measurements.

Our objective in developing the integrated protocol is to achieve simultaneous data exchange and location detection. The localization protocol consists of estimating distances and positioning. ROULA sends hello messages to estimate node distances, hence it can extract an overhead of routing protocol generated in the NWK layer.

Before discussing which routing protocol is suitable for the NWK layer, we first introduce the existing routing protocols. The routing protocol is one of the major issues in wireless multi-hop networks. In the Internet Engineering Task Force (IETF), the Mobile Ad-hoc Networks (MANET) Working Group [2] has been organized to address this issue.

There are mainly two types of routing protocols. One is a reactive protocol and the other is a proactive protocol. Ad hoc on-demand distance vector routing (AODV) [20] is one of the reactive protocols. In AODV, control messages are generated according to requests to detect and maintain the routes. Zigbee [1], which is sensor network product for the industry, uses the AODV protocol.

OLSR [21] is one of the proactive protocols. OLSR sends the control messages periodically to detect the shortest paths to nodes in the network. Nodes in OLSR select the MPR nodes as relay nodes. OLSR enables efficient flooding of messages by using MPR nodes.

Figure 6 shows both the OLSR and ROULA function modules. OLSR and ROULA exchange hello messages to find one-hop nodes. In addition, OLSR uses topology control (TC) messages to find the routes in the overall network. TC messages periodically flood the network, and thus they are compatible with the messages gathering local coordinates from all the nodes in the ROULA protocol.

We selected the OLSR protocol for the NWK layer. We are currently porting the ROULA protocol into the OLSR protocol. We are investigating how ROULA can be efficiently

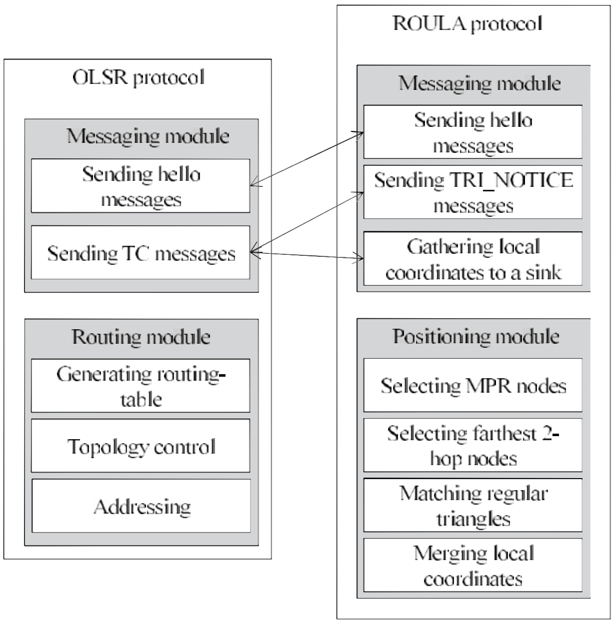

Figure 6: NWK function modules for integrated protocol. Arrows show compatibilities between OLSR and ROULA protocols.

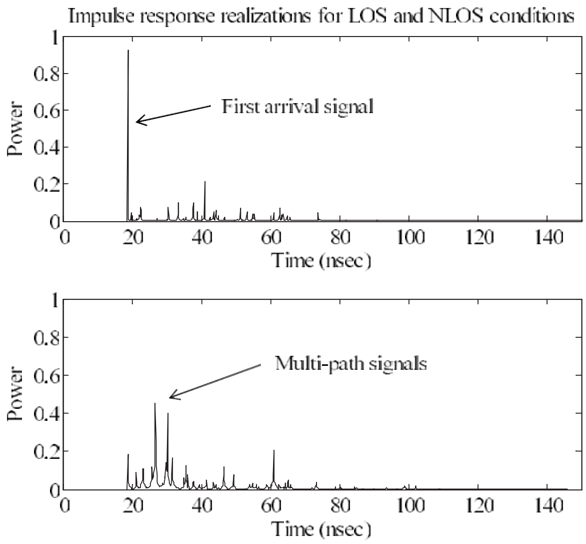

Figure 7: Time of arrival signals through LOS (top) and NLOS links (bottom).

integrated in the OLSR protocol [18], [19].

3 Target tracking application

3.1 Problem statement

The proposed integrated protocol can be used in such as equipment monitoring and security, emergency and logistics applications. Target tracking is an application of the integrated protocol. We focus on investigating target tracking using a ranging capability and describe how nodes on the integrated protocol are operated for target tracking.

One of the situations in which target tracking is used is inside a hospital. Target tracking allows for the position of tags with ranging capabilities to be monitored. Therefore, the positions of patients and doctors equipped with the tags are known at once even in emergency situations.

The problem with target tracking is how to estimate node positions sequentially. Although the problem to be solved is in a mobile node environment, we state the problem as a static location estimation for brevity.

Let us consider a two-dimensional positioning problem. Assume that at any time, the positions (x_i, y_i) for $i = 1...k$ reference nodes are known and the positions (x_i, y_i) for $i = k+1...n$ nodes are unknown. A typical location estimation using least-square is given by

$$\hat{p} = \arg\min \sum_{i=1}^{k} (r_i - \sqrt{(x_i - x)^2 + (y_i - y)^2})^2, \quad \text{for } k \geq 3, \qquad (2)$$

where $\hat{p}(x, y)$ is the estimated node position and k is the number of reference nodes. The range measurements obtained from TOA estimation is r_i. Equation (2) provides a good solution for the estimating the position when the range measurements are done through LOS links. However, once the range measurements are done through NLOS links, the estimated position will be biased.

Let us consider that the range measurements are

$$\hat{r}_i = r_i + \begin{cases} e_i^{los}, & i = 1, 2, ..., M \\ e_i^{los} + b_i^{nlos}, & i = M+1, ..., N \end{cases}, \qquad (3)$$
$$\text{where } e_i^{los} \sim \mathcal{N}(0, \sigma^2),\ b_i^{nlos} \sim \mathcal{E}(\mu).$$

LOS measurement noise e_i^{los} is modeled as a zero mean Gaussian distribution with variance σ^2. NLOS bias b_i^{nlos} is a positive distance bias introduced due to LOS blockage, and is modeled as an exponentially distributed random variable with mean μ.

Figure 7 illustrates some typical impulse response realizations for ranging at the receiver for LOS and NLOS conditions. In the case of a LOS link, the first arrival signal is normally precisely detected and it is identical to the shortest path signal of the sight (i.e. actual distance). However, when an obstruction blocks the LOS link, the first arrival signal received at the receiver may not be identical to the signal of the shortest path. Reflections from scatters are reached at the receiving nodes. Therefore the range measurement through a NLOS link results in introducing a bias error.

3.2 Cooperative target tracking

3.2.1 Notations and assumptions

Let us introduce the notations for the three nodes that we used in the proposal listed in Table 1. A target node (TN) is a node

Table 1: Notations for three nodes.

Notation	Description
Target node (TN)	Position should be tracked.
Mobile node (MN)	Relay for TN positioning
$\mathrm{RN_i} \mid i = 1 \ldots 3$	Position is known.

that should be tracked and estimated its position. A mobile node (MN) is a node that has the capability to move and has a role in assisting the TN tracking. A MN can be a human or a mobile robot. Reference nodes ($\mathrm{RN_i} \mid i = 1 \ldots 3$) are the nodes whose positions are known. Figure 8 shows the example topology of cooperative target tracking. In the target tracking, we make the following assumptions.

- TN, MN, and RN have TOA ranging capability.
- Identifications for LOS/NLOS links are achieved by using simple hypothesis testing of received signals in a mobile node environment [7].
- NLOS link is generated when an obstruction crosses a LOS link, as illustrated in Fig. 8.
- Both TN and MN are connected to three RNs, and TN is connected to MN.

3.2.2 Procedure

As discussed in Section 2.3, positioning accuracy is prioritized parameter for the integrated protocol. Introducing the positioning accuracy as a QoS parameter in the integrated protocol motivates the nodes in the network to cooperate for precise positioning. Conventional cooperative data relaying may introduce the delay because of data multi-hopping. However, we present here the cooperative relaying has a benefit for precise positioning. A cooperative target tracking using mobile nodes is then proposed to obtain precise positioning in an NLOS environment.

We describe the proposal by assuming static snapshot illustrated in Fig. 8. Three RNs, an MN, and TN are located on a field. The problem is to estimate the TN position. An obstruction is located between TN and $\mathrm{RN_2}$, resulting in the estimated position having bias due to the range measurement through the NLOS links. To avoid such a positioning situation that includes NLOS links, MN moves to an area to obtain LOS links from the TN and RNs when the TN has an NLOS link for positioning.

In Fig. 8, MN is located so that it has LOS links from the three RNs and TN. We describe an area that is guaranteed to obtain LOS links in Section 3.2.3. In this case, the RNs estimate the TN position by relaying the MN positioning. First, the RNs estimate the MN position with Equation (2) through LOS links of the indexes (1) as described in Fig. 8. Once MN obtains its own position, it is considered as a pseudo reference node. Then, $\mathrm{RN_1}$, $\mathrm{RN_3}$, and MN estimate the TN position with Equation (2) through the LOS links of indexes (2) as described in Fig. 8.

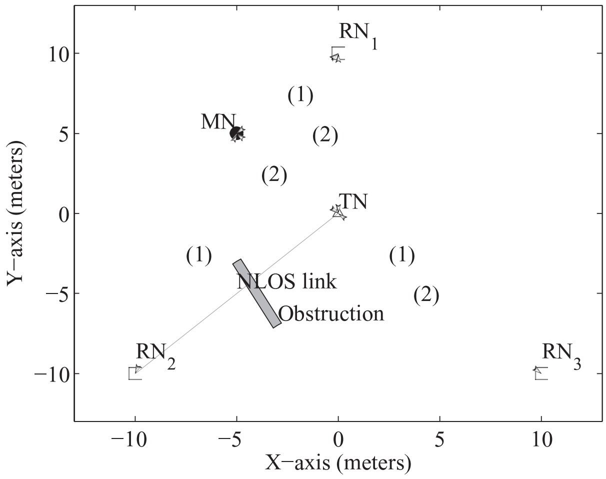

Figure 8: Illustration of target tracking. Messages are indexed in number order for cooperative target tracking.

Table 2: Notations for two methods.

Notation	Cooperation	Description
Conv.	No	Non-cooperative target tracking with only three RNs using EKF
Proposal	Yes	Cooperative target tracking with three RNs and a MN using EKF

3.2.3 Guaranteed area to obtain LOS links

To assist TN positioning, MN moves to the guaranteed area to obtain LOS links from three RNs and the TN. Figure 9(a) presents the guaranteed area to obtain LOS links from the three RNs. When the MN is placed in the shaded areas, it is guaranteed to obtain LOS links from the three RNs. Figure 9(b) presents the guaranteed area to obtain LOS links from the three RNs and the TN.

At present, we only consider a situation where the area to obtain LOS links from three RNs and a TN always exists, and the MN is placed that area.

To cope with general cases, we are investigating the following point:

- The condition for a guaranteed area where the LOS links can be obtained from k RNs and a TN (x, y), where $k \geq 3$, and x and y are variables.

4 Performance evaluation

4.1 Simulation setting

A performance evaluation through simulation proved the effectiveness of our proposed cooperative target tracking. We implemented extended Kalman filtering (EKF) [5] to estimate the moving TN positions. A node's motion can be considered

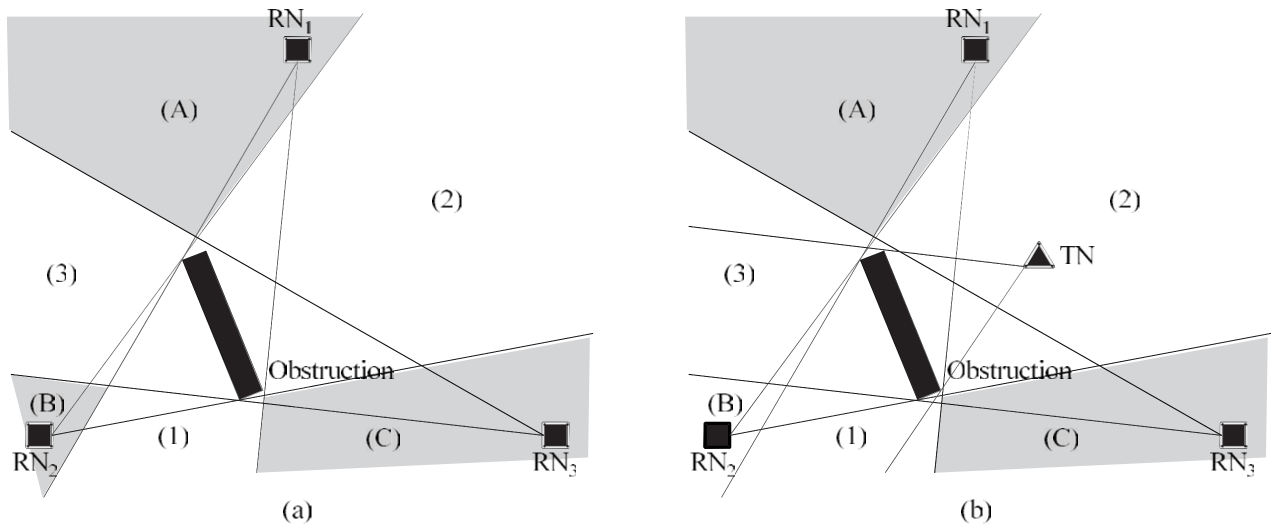

Figure 9: Illustration of areas (shaded) that are guaranteed to obtain LOS links from (a) three RNs and (b) three RNs and TN.

as a dynamic system for the function of time. Therefore, EKF can be applied to target tracking [5], [6].

Table 2 lists notations for two methods whose performances were compared. A conventional method represents non-cooperative target tracking using EKF that three RNs estimate moving TN through NLOS links. A proposed method represents cooperative target tracking using EKF that three RNs and MN jointly estimate moving TN through LOS links.

In addition, we implemented Cramer-Rao lower bound (CRLB). CRLB is the bound on a unbiased estimator [10]. This bound provides the best achievable performance [5]. Therefore, it can be used as a performance benchmark of the target tracking accuracy. Since covariance matrix of EKF in the absence of a process noise equation is identical to CRLB [11], we used the diagonal elements of the covariance matrix for calculating the CRLB.

4.2 Simulation results

The cooperative target tracking was performed by using a simulation. For LOS range measurement and NLOS bias error, we used $\sigma^2 = 0.1$ and $\mu = 1.6$ (m).

Figure 10 illustrates the topologies of the networks and estimated positions represented by triangles for the conventional method (left) and the proposed method (right). RNs are placed at $\mathrm{x}_1 = [0, 10]$, $\mathrm{x}_2 = [-10, -10]$, and $\mathrm{x}_3 = [10, -10]$ (m). The start point of TN is at $[0, 0]$ (m). TN moves in a straight line at a constant velocity of 1.0 (m/s). The observed time is 5 (s) with a sampling interval of 0.1 (s). The link between TN and RN_2 is blocked by the obstruction.

As shown in Fig. 10, the estimated positions using the conventional method had biased positioning errors from RN_2. We found that the estimated positions by the proposed method were much closer to the actual TN trajectories.

Figure 11 plots the cumulative distribution function (CDF) of the positioning errors that are defined as

$$\sqrt{(x_t - x_t^A)^2 + (y_t - y_t^A)^2}, \tag{4}$$

where (x_t, y_t) denotes the estimated position at time t and (x_t^A, y_t^A) denotes the actual position at time t. The conventional method had large positioning errors. The proposed method had less positioning errors and approached the CRLB.

Here, we only presented the one scenario. Various scenarios including several obstructions and random target motions will be investigated in the future. In addition to the positioning accuracy, the impact of delays in using the time slot for positioning in the MAC and data collections are needed to be considered.

5 Conclusion

We presented an overview of an integrated protocol for communications and positioning. The objective of this integrated protocol is to enable simultaneous data exchange and location discovery. We designed each layer of the integrated protocol. For the MAC layer, the resource control for positioning was introduced. For the NWK layer, we described the compatibility of OLSR with the localization protocol for enabling simultaneous routing and localization. We also discussed cooperative target tracking. Using a simulation, we found that cooperative target tracking achieved less positioning errors and approached the CRLB.

In future work, we will conduct detailed evaluations on node cooperation for precise positioning and implementation on simultaneous routing and localization.

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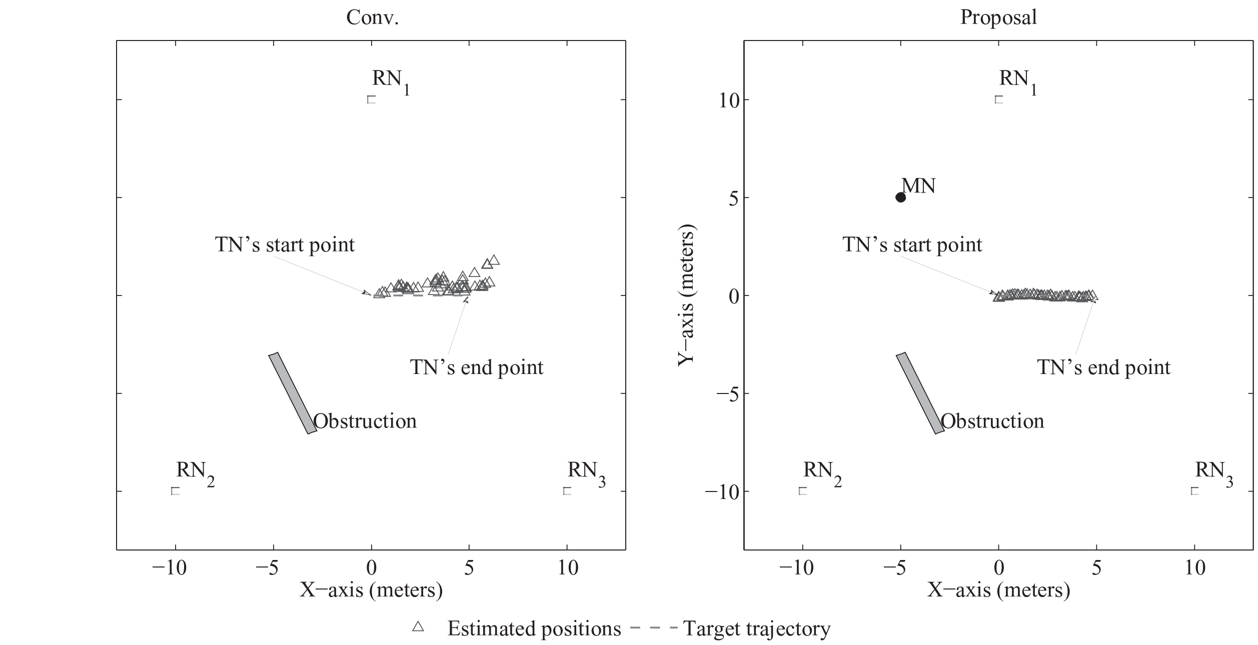

Figure 10: Estimated positions for conventional (left) and proposed (right) tracking methods.

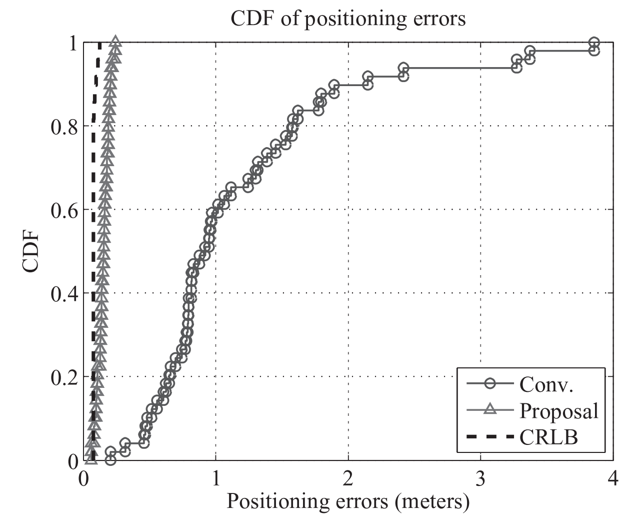

Figure 11: CDF of positioning errors.

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(Received October 15, 2008)
(Revised July 22, 2009)

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